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Cross section measurements of a narrow baryonic state decaying to $K_S^0\,p$ and $K_S^0\,\bar{p}$ in deep inelastic scattering at HERA

ZEUS Collaboration

Abstract

Recent results from the ZEUS experiment have provided evidence for a narrow baryon resonance decaying to $K_S^0\,p\,(\bar{p})$, interpreted as a pentaquark (antipentaquark). The measurement was performed in the central rapidity region of inclusive deep inelastic scattering at an ep centre-of-mass energy of 300-318 GeV for exchanged photon virtuality, Q^2, above 20 GeV^2. This study extends the previous analysis by presenting cross-section measurements for Θ^+ production and decay. The cross sections were compared in bins of $Q^2_{\rm min}$ to those of Λ baryons produced in the same kinematic region.

1 Introduction

Cross sections provide valuable information on the production mechanism of identified hadrons. Hence, a cross section measurement is especially important for the predicted pentaquark candidate, Θ^+, which has the quark content $udud\bar{s}$. This baryonic state has been observed by a number of experiments [1] in the K^+n and K^0_Sp invariant mass spectra, with a mass near 1530 MeV and a width close to the respective experimental resolutions.

The resonance decaying to K^0_Sp in ep collisions, reported by ZEUS [2], is the first evidence of a possible five quark state in the kinematic region dominated by fragmentation of quarks and gluons produced in high-energy colliding experiments. Therefore, information on the Θ^+ production rate in such an environment is especially significant. In this paper, Θ^+ baryon cross sections are reported along with their ratios to those of a more conventional three-quark baryonic state, $\Lambda(1116)$.

2 Experimental setup

ZEUS is a multipurpose detector described in detail elsewhere [3]. The main components used in the present study are the central tracking detector (CTD) and the uranium-scintillator calorimeter (CAL). The CTD [4] is a cylindrical drift chamber with nine super-layers covering a polar-angle[1] region $15^o < \theta < 164^o$ and a radial range $18.2 - 79.4$ cm. The transverse-momentum resolution for charged tracks traversing all CTD layers is $\sigma(p_T)/p_T = 0.0058p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV.

Surrouding the CTD is the CAL [5]. Longitudinally segmented into electromagnetic and hadronic sections, the CAL is divided into three parts: forward, barrel and rear. The energy resolution of the CAL under test-beam conditions is $\sigma_E/E = 0.18/\sqrt{E}$ for electrons and $\sigma_E/E = 0.35/\sqrt{E}$ for hadrons, with E in GeV.

The luminosity was measured using the bremsstrahlung process $ep \rightarrow ep\gamma$ with the luminosity monitor [6], a lead-scintillator calorimeter placed in the HERA tunnel at Z =-107m.

3 Data sample

The data sample corresponds to an integrated luminosity of 121 pb^{-1}, collected by HERA during the running period 1996-2000, at $\sqrt{s} = 300, 318$ GeV.

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left toward the center of HERA. The coordinate origin is at the nominal interaction point.

The analysis uses deep inelastic scattering (DIS) events measured with exchanged-photon virtuality $Q^2 \geq 20\,\text{GeV}^2$, as reported in the previous publication [2]. The Bjorken scaling variables x and y, as well as Q^2, were reconstructed using the electron method (denoted by the subscript e). In addition, both the double angle (DA) [7] and the Jacquet-Blondel (JB) [8] methods were used. While the first relies on the angles of the scattered electron or positron[2] and of the hadronic energy flow, the latter is based entirely on measurements of the hadronic system. The scattered-electron candidate was identified from the pattern of energy deposits in the CAL [9].

The following cuts were used to select DIS events:

- $E_{e'} \geq 10\,\text{GeV}$, where $E_{e'}$ is the corrected energy of the scattered electron measured in the CAL;
- $38 \leq \delta \leq 60\,\text{GeV}$, where $\delta = \sum E_i(1 - \cos\theta_i)$, E_i is the energy of the ith calorimeter cell, the smallest subdivision of the CAL, and θ_i is its polar angle with respect to the beam axis and the sum runs over all cells;
- a primary vertex position, determined from the tracks fitted to the vertex, in the range $\mid Z_{vertex} \mid < 50$ cm;
- $Q^2_e \geq 20\,\text{GeV}^2$;
- at least one secondary vertex in the event.

The charged tracks were selected in the CTD with transverse momentum, $p_T \geq 0.15\,\text{GeV}$ and pseudorapidity, $|\eta| \leq 1.75$, restricting this study to a region where the CTD track acceptance and resolution are high. The total number of K^0_S with $p_T(K^0_S) > 0.3\,\text{GeV}$ and $|\eta(K^0_S)| < 1.5$, identified using the $K^0_S \to \pi^+\pi^-$ decay mode, was 170,000. To eliminate contamination from $\Lambda(\bar{\Lambda})$ decays, candidates with a proton-pion mass hypothesis $\text{M}(\text{p}\,\pi) < 1121\,\text{MeV}$ were rejected.

The (anti)proton-candidate selection used the energy-loss measurement in the CTD, dE/dx. The $K^0_S p(\bar{p})$ invariant mass distribution was obtained by combining K^0_S candidates in the mass region $483 - 513\,\text{MeV}$ with (anti)proton candidates in the (anti)proton dE/dx band. Only primary-vertex tracks with more than 40 CTD hits were used to ensure a good dE/dx measurement. The tracks were then selected by requiring $f \leq dE/dx \leq F$, where f and F, motivated by the Bethe-Bloch equation, are the functions: $f = 0.35/p^2 + 0.8$, $F = 1.0/p^2 + 1.2$ (for positive tracks) and $f = 0.3/p^2 + 0.8$, $F = 0.75/p^2 + 1.2$ (for negative tracks), where p is the total track momentum in GeV. In addition, this band was restricted to $p < 1.5\,\text{GeV}$ and $dE/dx > 1.15$ mips in order to reduce the pion background. The CTD resolution for the $K^0_S\, p\, (\bar{p})$ invariant-mass near 1530 MeV, estimated using

[2] Hereafter, both e^+ and e^- are referred to as electrons, unless explicitly stated otherwise.

Monte Carlo simulations, was $2.4 \pm 0.2\,\text{MeV}$ for both the $K^0_S\, p$ and the $K^0_S\, \bar{p}$ channels. Figure 1 shows the $K^0_S\, p\, (\bar{p})$ invariant mass for different values of the minimum Q^2 cut for $Q^2 > Q^2_{\text{min}} = 20, 30, 40, 50\,\text{GeV}^2$.

For the cross-section ratio of $\sigma(\Theta^+ \to K^0 p)$ to $\sigma(\Lambda(1116))$, the Λ-baryons were selected in the decay mode $\Lambda \to p\pi^-$. All events were required to have at least one track selected with the dE/dx cut, exactly as in the reconstruction of the Θ^+ state[3]. The uncertainties in the Monte Carlo simulation of the dE/dx cancel in the ratio $\sigma(\Theta^+ \to K^0 p)/\sigma(\Lambda)$.

The Λ cross sections were also cross-checked using an independent selection in which all events were required to have at least one secondary vertex and the momentum of the proton candidate was required to be larger than that of the pion. The cross-sections calculated with the two methods agree within 5-12% and the difference was used in the estimation of the systematic uncertainties.

In the event that Monte Carlo simulation might not adequately reproduce the energy-loss measurement in the CTD, a comparison of the Λ cross sections obtained using the secondary-vertex method and the dE/dx method was used to estimate systematical uncertainties due to the latter method in the Θ^+ cross-section evaluation.

4 Cross sections and Monte Carlo simulations

The cross sections for $\Theta^+ \to K^0 p$ and Λ (and their antiparticles) were measured in the kinematic region $Q^2 \geq 20\,\text{GeV}^2$, $p_T > 0.5\,\text{GeV}$, $|\eta| < 1.5$ and $0.04 < y < 0.95$. The cross sections were determined by $N/(A \cdot \mathcal{L} \cdot BR)$ where N is the number of reconstructed Θ^+ or Λ events, A is the acceptance, $\mathcal{L}$ is the integrated luminosity and BR is the branching ratio. The acceptance is defined by the number of reconstructed $\Theta^+(\Lambda)$ divided by the number of generated $\Theta^+ \to K^0 p(\Lambda \to p\pi)$ and takes into account migrations, efficiencies and radiative effects. The branching ratios for $K^0 \to K^0_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^+$ were taken from the PDG [10].

The number of reconstructed Θ^+ events were determined using a fit with a three-parameter polynomial plus two gaussians with the width of the 1522 MeV Gaussian fixed to 6 MeV [2]. Fig. 1 shows the fit on top of the $K^0_S\, p\, (\bar{p})$ invariant-mass spectra. For Λ reconstruction, a single-gaussian fit was used with a second-order polynomial function for the description of the background.

The acceptances were calculated using the Rapgap 4.08 [11] and Ariadne [12] Monte Carlo (MC) models. The models were interfaced to Heracles 4.5.2 [13] in order to incorporate first-order electroweak corrections. The generated events were then passed

[3] The requirement that a track should originate from primary vertex was not used.

through a full simulation of the detector using GEANT 3.13 [14] and processed and selected with the same programs as used for the data.

The acceptance correction for Θ^+ was calculated using the RAPGAP model whereby Σ^+ baryons were assumed to be Θ^+ baryons with a mass of 1522 MeV, which were forced to decay, with 100% branching ratio, to the $K^0 p$ ($\bar{p}$) final state. The overall acceptance for $Q^2 \geq 20\,\text{GeV}^2$, $0.04 < y < 0.95$, $p_T > 0.5\,\text{GeV}$ and $|\eta| < 1.5$ for the Θ^+ was around 4%.

For the Λ-baryons, the ARIADNE model for fully inclusive DIS was used. The acceptance correction was found to be approximately 10%.

5 Experimental uncertainties

The systematic uncertainties on the measured cross sections were determined by changing the selection cuts or analysis procedure. The following sources were considered, with the uncertainty for the Θ^+ cross section, calculated for $Q^2_{\text{min}} = 20\,\text{GeV}^2$, given in parentheses:

- event reconstruction and selection. Systematic checks were performed by varying the cuts on y_{JB}, δ and the vertex position requirement ($< 5\%$). The electron method was replaced by the double angle method (+21%). Other DIS-selection cuts were found to have a negligible effect on the final cross sections;
- uncertainties related to the Θ^+ reconstruction. The width of the Gaussian distribution was not fixed (-6%). The double Gaussian fit was replaced by a single Gaussian fit (-17%). The bin size was raised and lowered by 1 MeV ($< 5\%$); the log-likelihood method was used for the fitting procedure instead of the χ^2 method ($< 3\%$). The Θ^+ p_T spectrum is harder for data than for MC simulation, hence the RAPGAP p_T distribution was re-weighted to obtain a good agreement with the measured spectrum (+11%).
- uncertainties related to both Θ^+ and Λ reconstruction. The dE/dx cut was increased to 1.2 mips (-12%). The maximum momentum of protons was increased to 1.7 GeV (+11%). The dE/dx band in the Monte Carlo was varied to match the momentum distribution in the data (+10%). The Λ cross section was reconstructed using the secondary vertex algorithm. The difference between Λ cross sections obtained using the dE/dx and the secondary-vertex methods was included in the Θ^+ cross section (-12%).

The overall systematic uncertainty was determined by adding the above uncertainties in quadrature. The normalisation uncertainties due to the luminosity measurement error, and those due to the Λ and K^0_S decay branching ratios [10] were not included in the systematic uncertainties.

6 Results

The cross section for the Θ^+ baryons and their antiparticles measured in the kinematic region given by $Q^2 \geq 20\,\mathrm{GeV}^2$, $0.04 < y < 0.95$, $p_T > 0.5\,\mathrm{GeV}$ and $|\eta| < 1.5$ was:

$$\sigma(e^\pm p \to e^\pm\, \Theta^+\, X \to e^\pm\, K^0 p\, X) = 125 \pm 27(\mathrm{stat.})^{+36}_{-28}(\mathrm{syst.})\ \mathrm{pb}.$$

Figure 2 shows the cross section integrated above Q^2_{min}. Figure 3 shows the ratio of this cross section to that of the Λ cross section integrated above Q^2_{min}, where the ratio, defined in the same kinematic region as above, is

$$\mathrm{ratio} = \frac{\sigma(e^\pm p \to e^\pm\, \Theta^+\, X \to e^\pm\, K^0 p\, X)}{\sigma(e^\pm p \to e^\pm \Lambda X)}.$$

This ratio, for $Q^2_{\mathrm{min}} = 20\ \mathrm{GeV}^2$, is $4.2 \pm 0.9(\mathrm{stat.})^{+1.2}_{-0.9}(\mathrm{syst.})\%$ and, in the current data, shows no significant dependence on Q^2_{min}. Since the Θ^+ has other decay channels in addition to $\Theta^+ \to K^0 p$, this ratio sets a lower limit on the production rate of the Θ^+ to that of the Λ-baryon.

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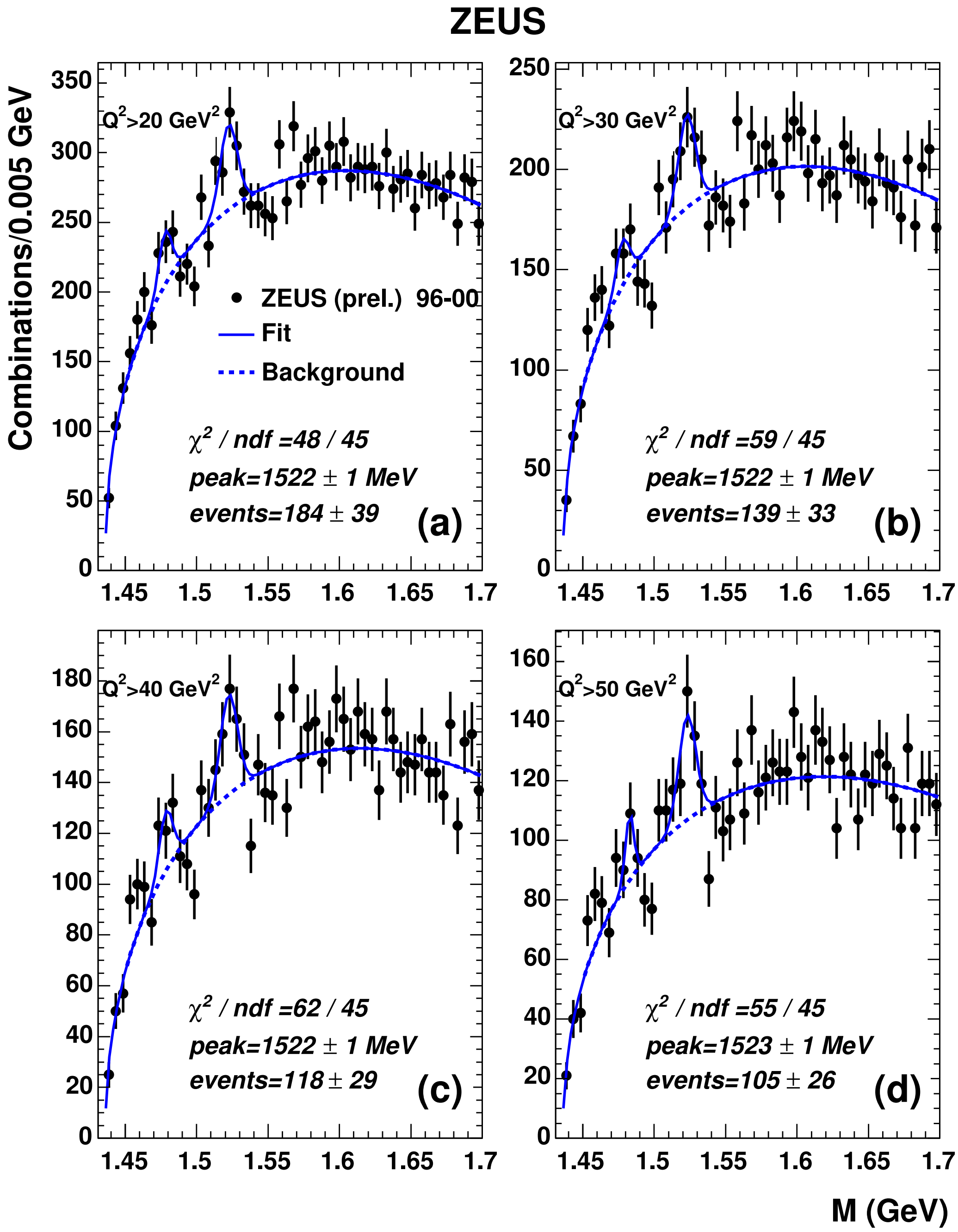

Figure 1: *Invariant-mass spectra for the $K^0_S\, p\, (\bar{p})$ channel as functions of Q^2_{min}. The solid line is the result of a fit to the data using a threshold background plus two Gaussians. The dashed line shows the background component of the fits. The width of the Gaussian describing the signal at 1522 MeV was fixed to 6 MeV.*

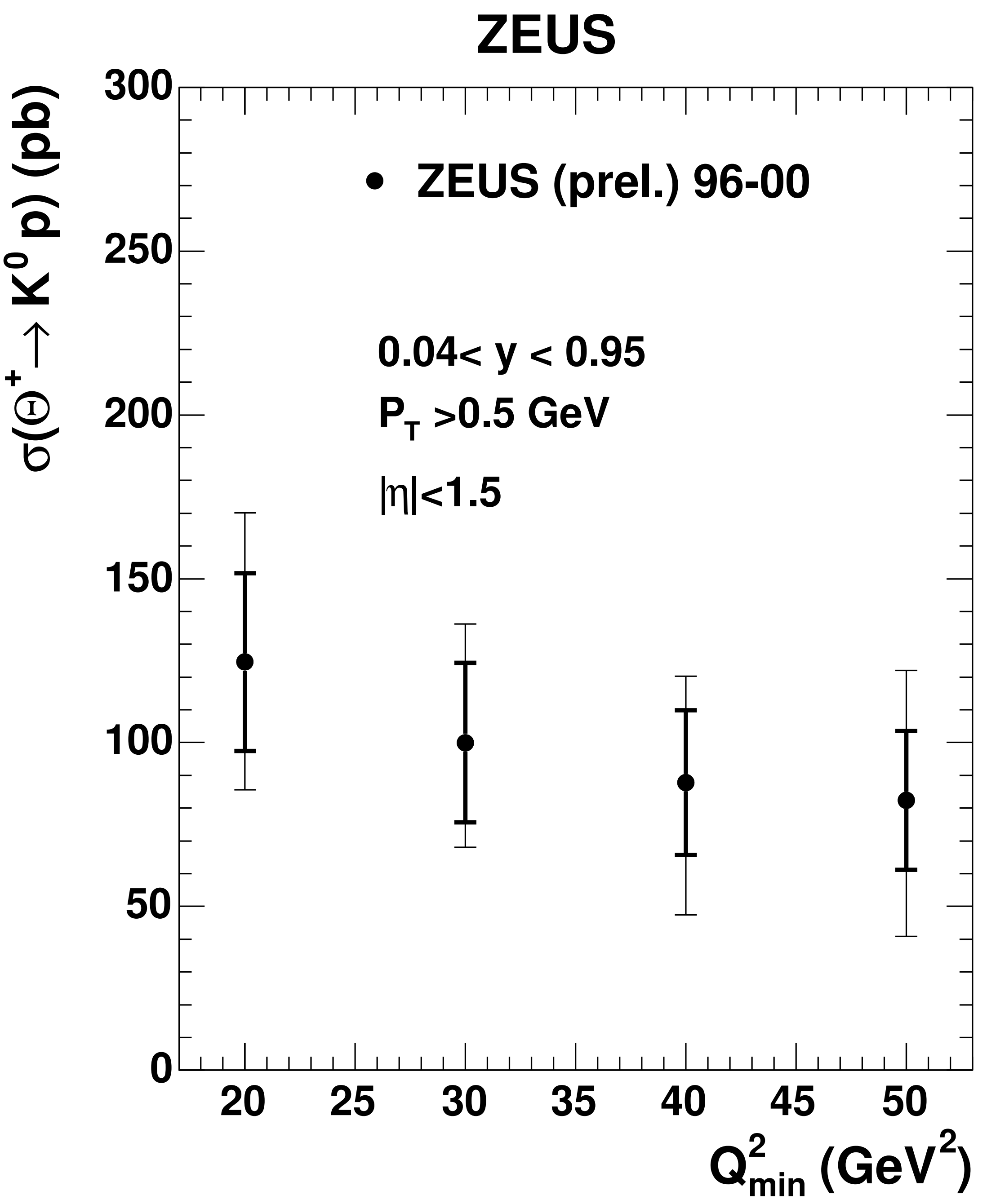

Figure 2: *Cross sections for the* $1522\,MeV$ *baryonic state decaying to* $K^0p\,(\bar{p})$*, measured in the kinematic region given by* $0.04 < y < 0.95$*,* $p_T > 0.5\,GeV$ *and* $|\eta| < 1.5$*, integrated above* $Q^2_{\min}$*.*

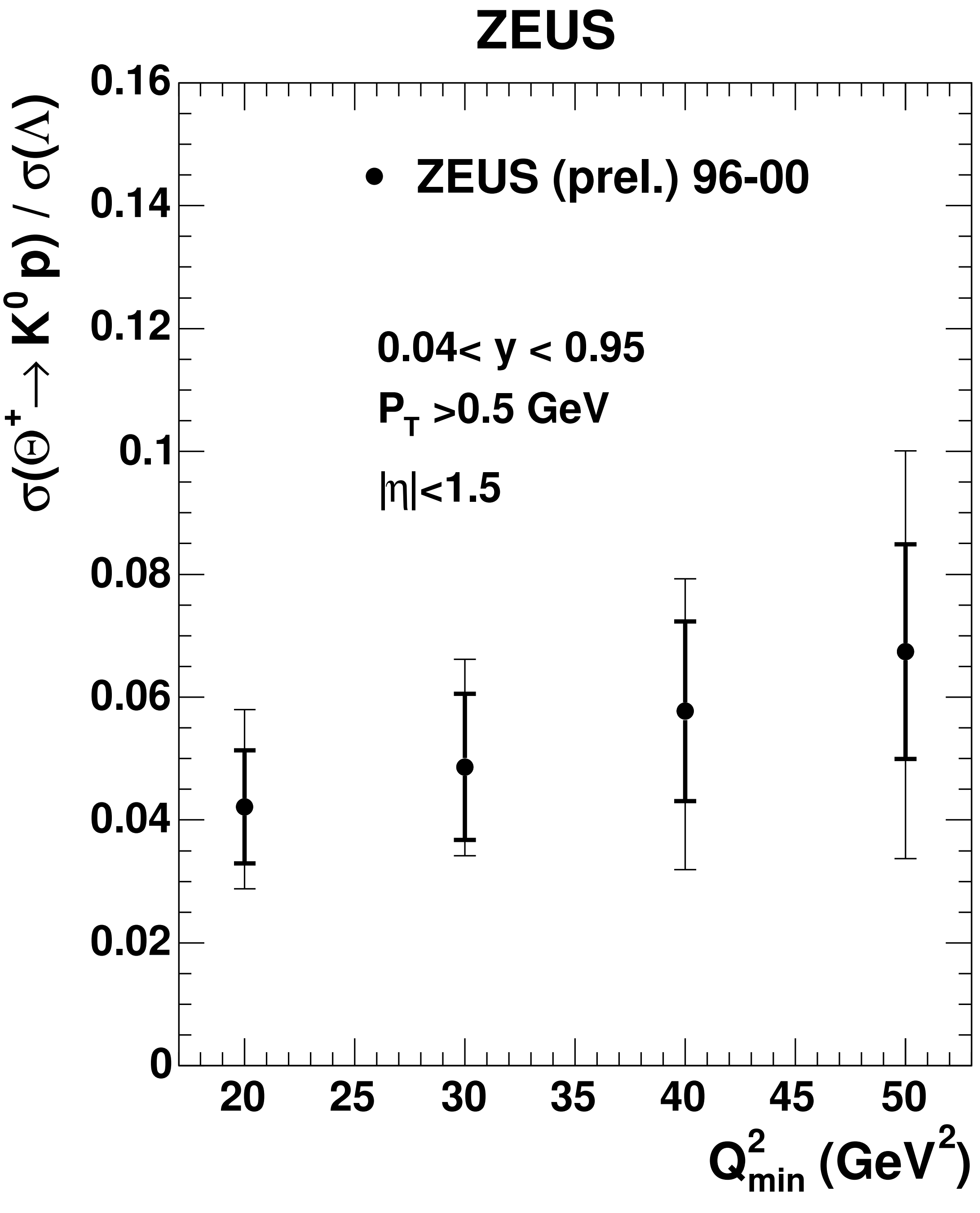

Figure 3: *Ratio of the cross section $\sigma(\Theta^+ \to K^0 p\ (\bar{p}))$ shown in Fig. 1 to the inclusive Λ cross section, $\sigma(\Lambda + \bar{\Lambda})$, measured in the kinematic region given by $0.04 < y < 0.95$, $p_T > 0.5$ GeV and $|\eta| < 1.5$, integrated above $Q^2_{\min}$.*